Review of Neutrino Oscillation Experiments

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Several experiments have sought evidence for neutrino mass and mixing via the phenomenon of neutrino flavor oscillations. In a three neutrino model, these oscillations are described by three angles, two mass splittings, and one CP violating phase. Experiments using neutrinos from the Sun, the atmosphere, nuclear reactors, and particle accelerators have gathered considerable information on these angles and splittings. Two of the three angles are known to be large: $\theta_{12} \simeq 33^\circ$, $\theta_{23} \simeq 45^\circ$, and an upper limit is known on the third, $\theta_{13} < 10^\circ$. Likewise, the mass splittings are known to fall in the range $\Delta m^2_{12} \simeq 8 \times 10^{-5}$ and $|\Delta m^2_{23}| \simeq 2.4 \times 10^{-3}$ eV^2. Several questions remain: the sign of the 2–3 mass splitting, the size of the unknown angle θ_{13}, and the size of the CP violating phase are yet to be measured. Also, a report of short-baseline $\bar{\nu}_e \to \bar{\nu}_m u$ oscillations has yet to be confirmed. These open questions are the target of an experimental neutrino oscillation program currently underway. This report will attempt to summarize the current state of neutrino oscillation measurements and the future program in as succinct a manner as possible.

1. Introduction

There is now in hand considerable evidence for neutrino flavor oscillations, and hence neutrino mass and mixing. Neutrino oscillations are determined by 6 parameters: two mass splittings, Δm^2_{12} and Δm^2_{23}, and 3 angles θ_{12}, θ_{23}, θ_{13}, and one CP violating phase δ:

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} 1 & & \\ & c_{23} & s_{23} \\ & -s_{23} & c_{23} \end{bmatrix} \begin{bmatrix} c_{13} & & s_{13}e^{-i\delta} \\ & 1 & \\ -s_{13}e^{i\delta} & & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & \\ -s_{12} & c_{12} & \\ & & 1 \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} \quad (1)$$

Knowledge of the first and last of these matrices is derived from measurements of solar neutrinos, reactor neutrinos, neutrinos from the atmosphere, and neutrinos produced at accelerators. Currently, there is no measurement which shows that the middle matrix is different from unity and this matrix is the focus of a future program of measurements. In this report, I will review the experimental measurements of the parameters controlling neutrino oscillations.

2. Current experimental status

2.1. θ_{12} and Δm_{12}

Knowledge of the oscillation parameters θ_{12} and Δm^2_{12} come from observations of $\nu_e \to \nu_\mu + \nu_\tau$ oscillations using neutrinos from the Sun and $\bar{\nu}_e \to \bar{\nu}_\mu + \bar{\nu}_\tau$ using neutrinos from nuclear reactors.

The Sun produces an enormous flux of electron neutrinos ranging in energy from a few keV up to several MeV in energy. These have been detected on Earth by radio-chemical experiments including Homestake [1], GALLEX [2], GNO [6, 7], and SAGE [3, 4] (see also the summary in [5]) and by the real-time water Cherenkov experiments Kamiokande, Super–Kamiokande (SK) [8, 9, 10, 11, 12, 13, 14, 15], and the Sudbury Neutrino Observatory (SNO) [16, 17, 18, 19]. Results of these experiments are summarized in Table I. Each of these experiments observes a deficit

Table I Summary of solar neutrino results. Rates are quoted in units of SNU's, fluxes in units of $10^6\nu/\mathrm{cm}^2/\mathrm{s}^2$.

Energy	Measurement	Expected
>0.233 MeV	$R = 67.4^{+2.6}_{-2.3}$	127^{+12}_{-10}
GALLEX+GNO+SAGE		
>0.813 MeV	$R = 3.23 \pm 0.68$	8.2 ± 1.8
Homestake		
5-20 MeV	$\phi_{\mathrm{ES}} = 2.35 \pm 0.02 \pm 0.08$	5.79 ± 1.33
SK	$A^{\mathrm{ES}}_{\mathrm{DN}} = -0.021 \pm 0.020^{+0.013}_{-0.012}$	0
SNO	$\phi_{\mathrm{ES}} = 2.35 \pm 0.22 \pm 0.15$	5.79 ± 1.33
	$\phi_{\mathrm{tot}} = 4.94 \pm 0.21^{+0.38}_{-0.34}$	5.79 ± 1.33
	$A^{\mathrm{ES}}_{\mathrm{DN}} = 0.146 \pm 0.198 \pm 0.033$	0
	$A^{\mathrm{CC}}_{\mathrm{DN}} = -0.056 \pm 0.074 \pm 0.053$	0
	$A^{\mathrm{NC}}_{\mathrm{DN}} = 0.042 \pm 0.086 \pm 0.072$	0

of ν_e's relative to expectations based on solar models (eg. [20, 21, 22, 23]). Confirmation that these deficits are due to a flavor-changing process (ie. oscillations) by the SNO experiment. SNO uses 1 kt of D_2O allowing separate measurements elastic ($\nu_x + e^- \to \nu_x + e^-$), charged-current ($\nu_e + d \to p + p + e^-$), neutral-current ($\nu_x + d \to p + n + \nu_x$) scattering rates. From these measurements, SNO has been able to confirm that the total neutrino flux, $\phi_e + \phi_\mu + \phi_\tau$, from the Sun was consistent with solar models and that the deficit of ν_e's was compensated by a non-zero flux of ν_μ ν_τ (Figure 2.1).

Interpretations of the deficits in terms of neutrino oscillations historically fell into four categories in the mass-splitting-mixing parameter space: vacuum oscillations ("VAC") $\Delta m^2_{12} \simeq 10^{-10}$ eV^2, "LOW" $\Delta m^2_{12} \simeq 10^{-7}$ eV^2, small mixing angle ("SMA")

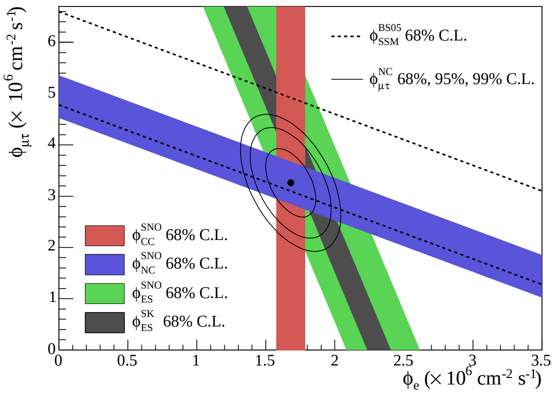

Figure 1: Neutrino fluxes measured by the SNO and SK experiments. The exclusively CC and NC channels observed by SNO allow for extraction of the ν_e and non-ν_e components of the electron neutrino flux. These results are consistent with the measurements made by SK using CC and NC elastic scattering. The total neutrino flux is consistent with predictions from solar models. Reprinted from [19].

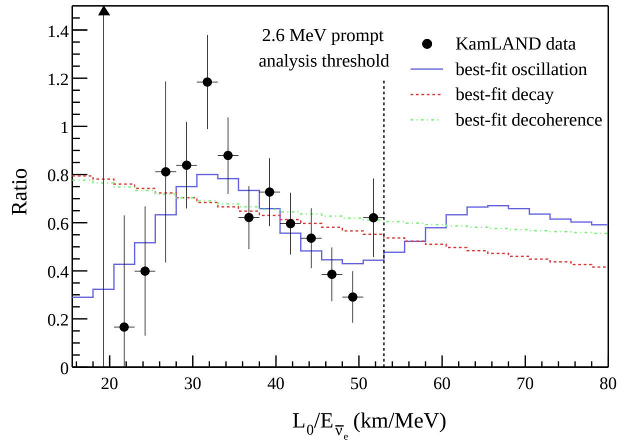

Figure 2: The KamLAND event rate relative to non-oscillated expectations as a function of reconstructed L/E. The solid curve is for LMA oscillation parameters. Dashed curves show non-oscillation models and are shown to give some indication as to the significance of the dip near 50 km/MeV. Reprinted from [25]

$\Delta m^2_{12} \simeq 10^{-5}$ eV^2, $\tan^2\theta_{12} \simeq 10^{-3}$, and large mixing angle ("LMA") $\Delta m^2_{12} \simeq 10^{-5-4}$ eV^2 $\tan^2\theta_{12} \simeq 0.4$. Each region has its own expected signatures: vacuum oscillations should produce an annual variation as the Earth-Sun distance varies throughout the year, the small-mixing solution should produce a significant spectral distortion in the energy region below 5 MeV; in many cases there is expected to be a significant matter effect from the Earth resulting in a day-night flux asymmetry. A preference for the LMA solution began to emerge from the Super–Kamiokande data which saw no significant spectra distortion of the recoil electron energy spectrum and no significant day-night asymmetry – a trend which was strengthened by the SNO measurements. Note that as the LMA solution produces a large matter effect on the oscillations in the Sun, the sign of the 1–2 mass splitting is determined to be positive by the solar neutrino data.

The validity of the LMA interpretation of the solar neutrino fluxes was demonstrated conclusively by the KamLAND experiment [24, 25]. KamLAND uses 1 kt of liquid scintillator located in the former Kamiokande cavern to observe $\bar{\nu}_e$'s from over 50 nuclear reactors located throughout Japan and Korea via inverse beta decay. The majority of the neutrino flux (79%) comes from 26 reactors located at distances ranging from 138-214 km resulting in an average distance of 180 km. The long baseline coupled with the low neutrino energy (10–50 MeV) allows KamLAND to test the solar LMA solution in a terrestrial experiment. KamLAND observes a deficit of neutrinos who's distribution in L/E is consistent with LMA oscillations (Figure 2). The parameters favored by the solar neutrino and KamLAND data are not only consistent with each other, but complement each other as the solar neutrino observations are mostly sensitive to the mixing parameter and the KamLAND measurements are most sensitive to the mass-splitting. Figure 3 summarizes the regions of θ_{12} and Δm^2_{12} favored by the combined solar and KamLAND data.

2.2. θ_{23} and $|\Delta m^2_{23}|$

Atmospheric neutrinos are produced in cascades initiated by cosmic-rays collisions with nuclei in the Earth's atmosphere. The largest production mechanism is $\pi^+ \to \mu^+ + \nu_\mu$, $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ and charge-conjugates. While absolute rates of atmospheric neutrino production have large ($\simeq 20\%$) uncertainties, the relative rates of ν_e and ν_μ can be predicted with 5% accuracy and the fluxes are expected to be up/down symmetric with respect to the detector horizon. Several experiments have observed atmospheric neutrinos [26, 27, 28], however, few experiments rival the high statistics of the SK experiment. SK has collected contained ν_e and ν_μ events ranging in energy from 100 MeV through 20 GeV [29, 30, 31] and upward-going neutrino-induced muons ranging in energies from 20 GeV to 100 GeV [32, 33]. This data set, which spans roughly four orders of magnitude in neutrino energy, exhibits a significant zenith-angle dependent deficit of ν_μ's which is well described by neutrino oscillations [35]. Additionally, SK has isolated a high-resolution data sample which shows hints of an oscillatory L/E distribution [34]. Fits to this data yield results in the range $1.5 \times 10^{-3} < |\Delta m^2_{23}| <$

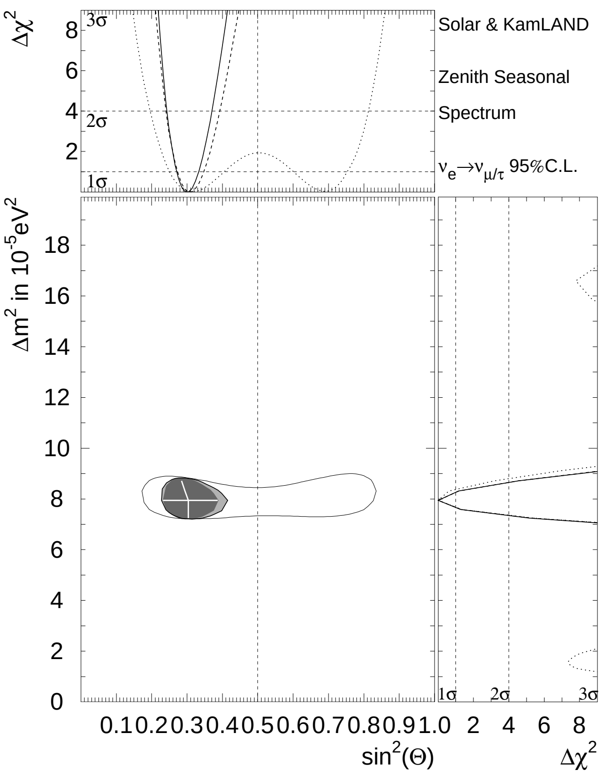

Figure 3: The allowed values of $\sin^2\theta_{12}$ and Δm^2_{12} at 95% C.L. The solid contour is for the KamLAND data alone. The light gray region adds solar neutrino data from SNO and SK and the dark gray region adds data from radiochemical experiments. Projections of the $\Delta\chi^2$ surfaces onto the horizontal and vertical axes are shown at the top and side. Reprinted from [15].

3.4×10^{-3} eV^2, and $\sin^2 2\theta_{23} > 0.92$ (90% CL).

The atmospheric neutrino results obtained by Super–Kamiokande have been confirmed by the K2K experiment [36, 37]. K2K uses a 98% pure beam of $\nu_\mu + \bar{\nu}_\mu$ of mean energy 1.3 GeV produced at the KEK 12 GeV PS. The beam is directed at the SK detector a distance of 250 km from the source. The experiment ran between 2001 and 2005 collecting a total of 1.049×10^{20} POT. The experiment has recorded 112 events with an expectation of 159 before oscillations – a 4.2 σ deficit. From fits to the energy spectrum of the 58 events which have a single muon (see Figure 6), K2K extracts a measurement of the oscillation parameters $\sin^2 2\theta_{23} > 0.56$ and $|\Delta m^2_{23}|$ in the range from $1.88 - 3.48 \times 10^{-3}$ eV^2 (90% CL), in good agreement with the SK atmospheric neutrino results.

Recently, the MINOS experiment has completed its first year of running with the NuMI neutrino beam from Fermilab. During this run, MINOS accumulated over 10^{20} protons on target and currently has enough data to improve on SK's measurement of Δm^2_{23}. Details of this new measurement are contained in these proceedings [38].

2.3. θ_{13}

Both solar and atmospheric oscillations show evidence for large neutrino mixing. One might also expect, then, that the remaining mixing angle, θ_{13} would also be large. However, to date no observation of oscillations involving this angle have been made. The most sensitive search has been made by the CHOOZ experiment [39] which looked for evidence of $\bar{\nu}_e$ disappearance at the Δm^2_{23} scale. The comparison of the measured to the expected positron spectrum is shown in Figure 2.3. No evidence is seen for an oscillation and CHOOZ has set an upper limit on $\sin^2 2\theta_{13}$ randing from 0.10 at the upper end of the Δm^2_{23} range indicated by atmospheric neutrinos to 0.15 at the lower end of that range. The CHOOZ results have been confirmed, although with less sensitivity, by the K2K experiment which has looked for ν_e appearance in their ν_μ beam [40]. They find one event with an expected background of 1.7 events setting a limit of roughly $\sin^2 2\theta_{13} < 0.26$. Recently, SK has examined their multi-GeV electron neutrino data for evidence of matter-enhanced oscillations in a search for non-zero θ_{13} [41]. No evidence is found, placing a limit on $\sin\theta_{13} < 0.06$.

2.4. LSND and miniBooNE

In 1996 the LSDN collaboration reported evidence for appearance of $\bar{\nu}_e$ in a $\bar{\nu}_\mu$ beam produced via muon decay in flight and at rest [42, 43, 44]. This result was not confirmed KARMEN, a similar, though somewhat less sensitive experiment [45, 46]. The short baseline of the LSND experiment, coupled with the relatively low neutrino energies ($\simeq$10-50 MeV) suggests that these oscillations are associated with a mass-splitting on the order of 1 eV^2. This splitting is difficult to reconcile with the atmospheric and solar neutrino oscillations which indicate a mass splitting more that two orders of magnitude smaller. Attempts to explain the solar and atmospheric neutrino oscillations and include the report from LSND typically rely on extensions to the standard model including models with a fourth, light, sterile, neutrino or CPT violations. Confirmation of the LSND result would be a major revolution in neutrino physics and is being pursued by the miniBooNE experiment at Fermilab [47].

3. Future experiments: θ_{13}, sign of Δm^2_{23}, and $\delta_{\rm CP}$

The future neutrino oscillation program seeks as its ultimate goal evidence for CP violation in the lepton sector. As can be seen from Eq. 1, any CP violation

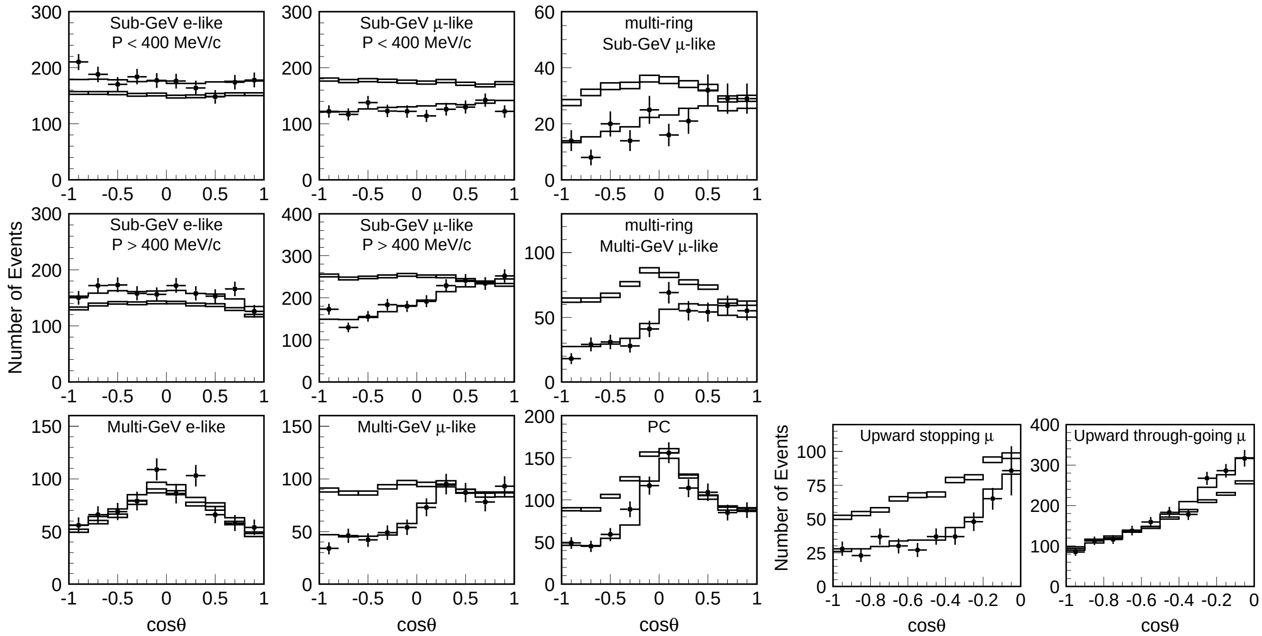

Figure 4: Zenith rates of atmospheric neutrinos observed by SK. The left most panels show the electron neutrino rates as a function of energy; central panels show the contained and partially-contained muon neutrino event rates, and the right most panels show the upward stopping and upward through-going muon rates. In each case, the data is shown by points, the expectations without oscillations are shown by boxes, and the best-fit oscillated rates are shown by a single line.

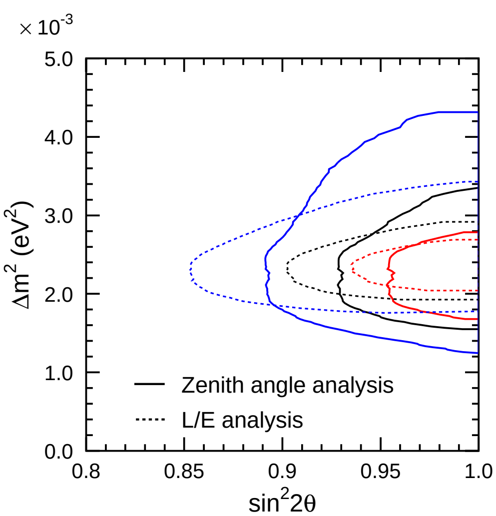

Figure 5: Allowed parameter region from the SK atmospheric neutrino results. Results are shown separately for the zenith-angle analysis and the high-resolution L/E analysis.

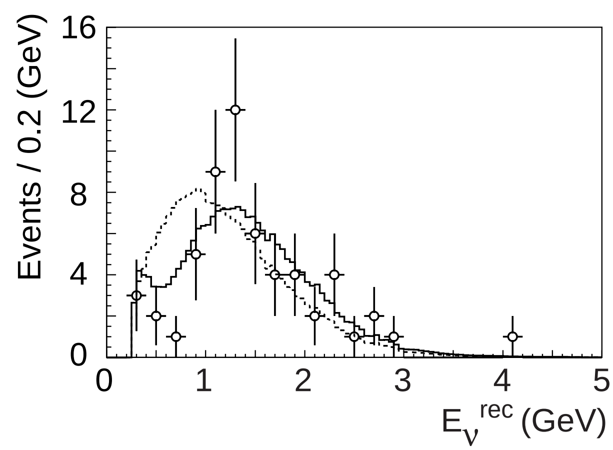

Figure 6: The muon neutrino spectrum observed by the K2K experiment.

enters into the neutrino mixing matrix proportional to $\sin\theta_{13}$. Since there is currently only an upper limit on this mixing parameter it is the focus of the next round of neutrino oscillation measurements to be carried out at reactors and accelerators.

3.1. Future experiments at reactors

There is current great interest in pushing the measurement technique used by the CHOOZ experiment to gain roughly an order of magnitude more sensitivity to $\sin^2 2\theta_{13}$. These include the Double-CHOOZ [48] experiment, KASKA [49], and Daya Bay [50] exper-

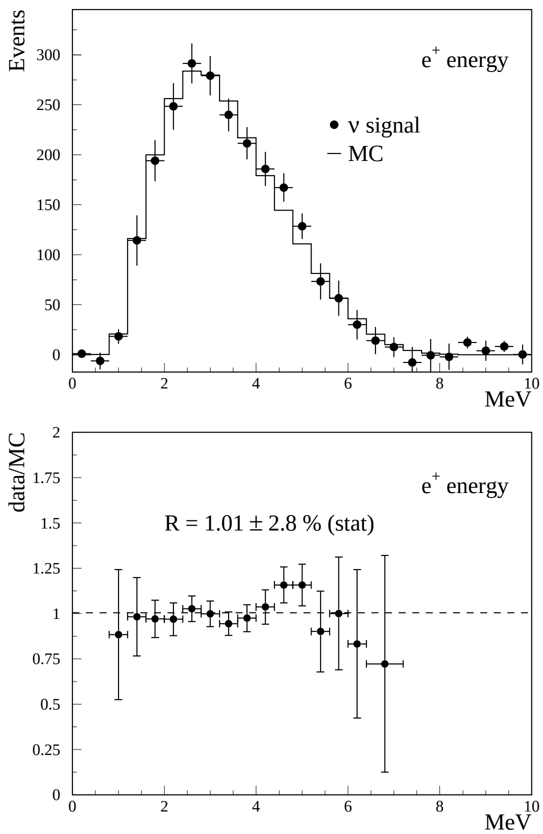

Figure 7: The comparison of the expected positron spectrum and the observed spectrum in the CHOOZ experiment. Top is the rate distribution and bottom shows the ratio.

iments. The main improvement sought by each of these experiments is to make relative measurements between identical (or nearly identical) detectors located at different distances from the reactor core to cancel uncertainties in the absolute neutrino production rates. The experiments expect to reach a sensitivity to $\sin^2 2\theta_{13}$ down to roughly 0.01. As these experiments measure $\sin^2 2\theta_{13}$ via s disappearance channel, they are insensitive to the affects of the CP violating phase δ.

3.2. Future experiments at accelerators

Two experiments are going forward to search for electron neutrino appearances in a muon neutrino beam. In Japan, a new neutrino beamline is under construction at the 50 GeV PS at J-PARC which is directed at the SK detector 295 km away for the T2K experiment [51]. In the first phase of the experiment is expected to begin in 2009 with a beam intensity of 100 kW ramping up to 0.9 MW by 2011. In its first run, T2K expects to have sensitivity to $\sin^2 2\theta_{13}$ down to roughly 0.006 (90% CL). Future upgrades include an increase in the beam intensity to 4 MW and construction of a new mega-ton scale water Cherenkov detector. With these upgrades, it will be possible to begin to study of CP violation.

In the US, the NOvA [52] experiment plans to construct a new 25 kt scintillator tracking calorimeter at a distance 810 km from the existing NuMI beam line. In its first run, NOvA plans to run 3 years in neutrino mode, and 3 year in anti-neutrino mode yielding a sensitivity to $\sin^2 2\theta_{13}$ down to roughly 0.008 (2σ). Due to its long baseline, NOvA is sensitive to the sign of Δm^2_{23} and can begin to study the question of the mass hierarchy in its first run. Later upgrades are imagined for NOvA, including the possibility of a multi-kt liquid Argon detector located at the second oscillation maximum and upgrades of the proton source increasing the reach of the mass hierarchy measurement and opening the possibility of searches for CP violation. Due to the large difference in baselines (295 km vs. 810 km), the combination of the data from T2K and NOvA greatly extend the search for CP violation beyond what can be accomplished by one experiment working alone.

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